SHUM YIP UPPERHILLS UHPC FACADE PANELS: ANALYSIS OF THE DESIGN PROCESS

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Abstract

This paper has been drawn up in the framework of the construction studies for the UHPFRC panel for Shum Yip Upperhills, built at Shenzhen, in China. The UHPFRC Material used is Organic fibers DUCTAL® FO with local reinforcement. The paper seeks to follow the conceptual design, reconstructing the decision-making process.

Résumé

Cet article a été élaboré dans le cadre des études pour la conception de panneaux BFUP (projet Shenye Upperhills), construit à Shenzhen, en Chine. Le matériau utilisé est le BFUP à fibres organiques DUCTAL® FO localement renforcé. L'article propose de reconstituer le processus de conception de la solution technique.

1. GENERAL PRESENTATION

The UHPFRC façade panels are designed for Shum Yip Upperhills Loft, a program which includes housing, offices, shopping malls and cultural spaces (Fig. 1). The overall project is designed by Urbanus (Shenzhen, China) and the façade is built by the contractor E-Grow (Shanghai, China). The total surface of the curtain wall is more than 20000 m², the dimension of a typical panel is 1.5 m (width) x 2.8 m (height). The Material used is UHPFRC Organic Fibers DUCTAL® NaW3 FO without Thermal Treatment partially reinforced with rebars.

Figure 1: Site view and perspective view of the façade (Source: Urbanus)

The paper wants to present a knowledge engineering approach, reconstructing the decision-making process. The following questions will be discussed:

- How the differences between design objectives and calculation and technological constraints, affect the quality of the object itself?
- What can be a proper coordination among the design stages to achieve high quality with cladding design using Organic Fibers UHPC?
- What kind of knowledge is used?

2. ORGANIC FIBERS ULTRA HIGH-PERFORMANCE CONCRETE DESIGN PROCESS

The Domain of use UHPFRC/Ductal® FO is mostly cladding elements, non-structural panels, shaping device, stair tread and eventually stair cases. Due to very few design recommendations the calculation design method applied to define reference stress value for the unreinforced UHPFRC/Ductal® FO is characterized as follows:

- Step one: an average tensile bending stress is evaluated from a thin element
- A safety coefficient of 3 is applied on this value on the elastic range.

From this hypothesis, the constitutive law displayed Fig. 2 can be used at Service Limit State.

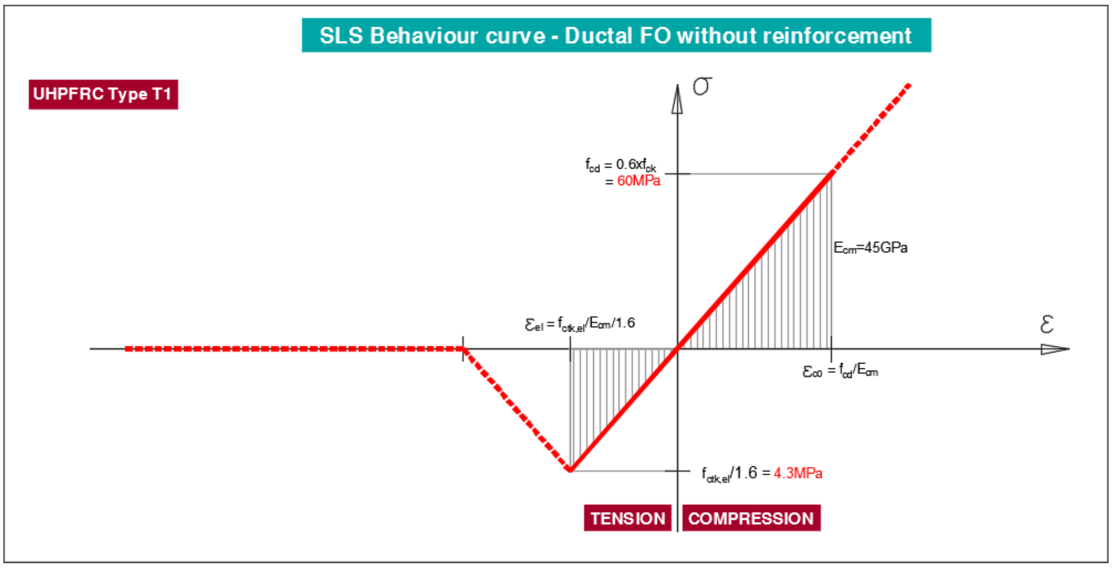

Figure 2: SLS constitutive curve – Ductal® FO without reinforcement

When the UHPFRC/Ductal® FO is reinforced the constitutive curve at the Service Limit State (SLS) is defined (Fig. 3) with an instantaneous elastic modulus (E_{cm} = 45,000 MPa). The design method is characterized as follows:

- A linear elastic stage limited by a stress value $f_{ctk,\,el}$
- A post-cracking stage characterized by a stress-crack width law.
- The verification should be carried out at the Service Limit State and at the Ultimate Limit Service

This approach is stipulated for concrete reinforced with metal fibers in the NF P18-710 [1], which is not the case for UHPFRC/Ductal FO, however, this approach helps to develop an understanding of the design rules with a « strain softening law » due to the addition of fibers.

According to the identity card of Ductal NaW3 FO STT [2], the material follows a strain softening law T1. This method is giving the following constitutive curves at Service Limit State (Fig. 4) and Ultimate Limit State (Fig. 5).

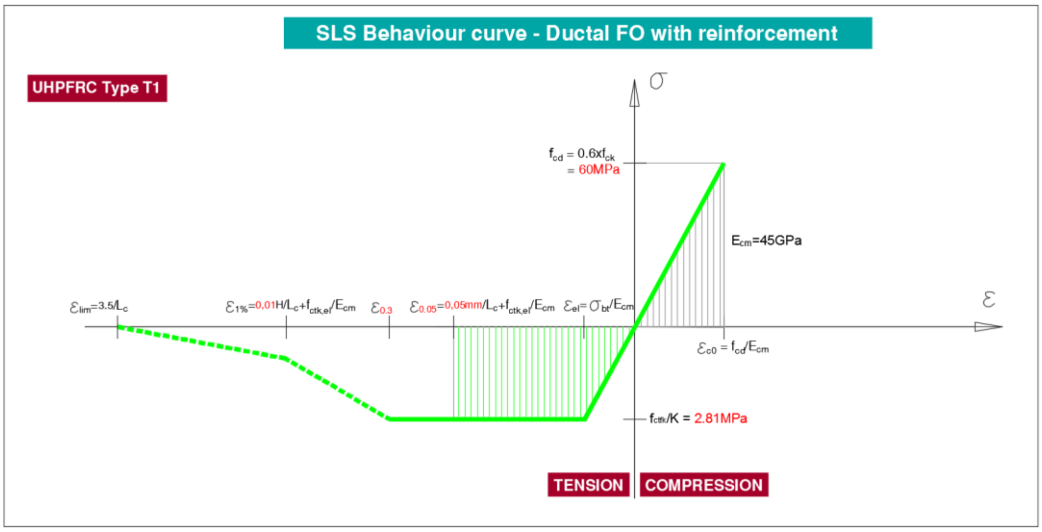

Figure 3: SLS constitutive curve – Ductal FO with reinforcement

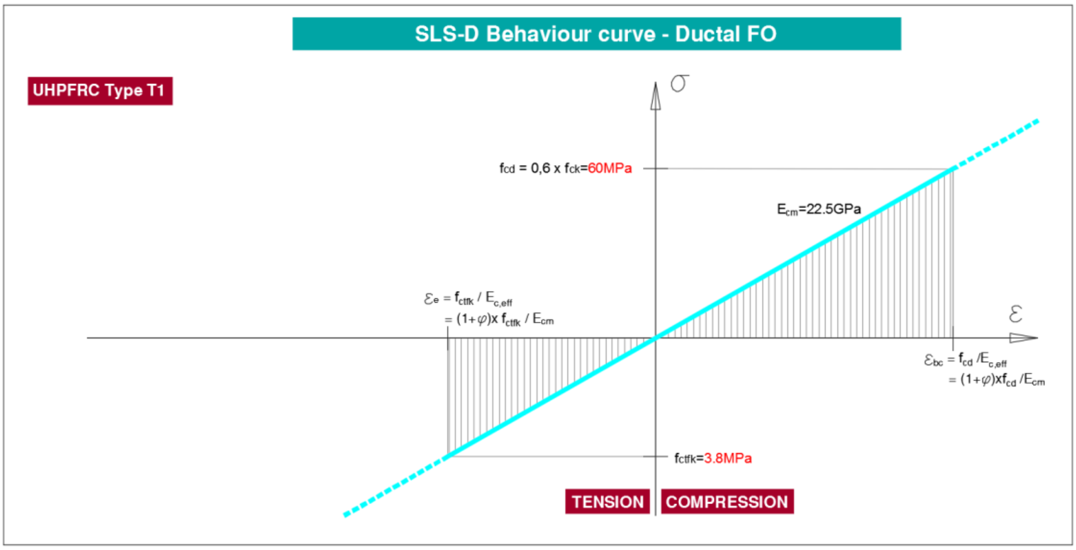

Figure 4: SLS-D constitutive curve – Ductal FO

The tensile plastic stage is limited to elongation $\varepsilon_{(0,05mm)} = 0{,}05mm / L_C + f_{ctk,el} / E_{cm}$ with $L_C = 2/3h$ with limitation of crack opening 0.05mm and limitation of compressive strain to $\varepsilon_{c0} = 1.33‰$.

The constitutive curve at the Service Limit State according to Displacement (**SLS-D**) is established with a delayed elastic modulus ($E_{c,eff}$ = 22,500 MPa).

The verification takes account of concrete creep by an affine transformation of the behaviour curve according to a coefficient $(1+\varphi)$, The value recommended by Lafarge for the coefficient φ is 1.0 without heat treatment [2]. The delayed elastic modulus of the DUCTAL® FO is divided by 2,0 ($E_{c,eff}$ = 22,500 MPa) in relation to the instantaneous modulus.

The constitutive curve at the ultimate limit state (**ULS**) is defined with an instantaneous elastic modulus (E_{cm} = 45,000 MPa). The tensile plastic stage of the DUCTAL® FO is limited to elongation: $\varepsilon_{(0,3mm)} = 0{,}3mm/L_C + f_{ctk,el}/(E_{cm} \times \gamma_{cf}) \leq 10‰$ with $L_C = 2/3h$ (see NF P18-710 §3.1.7.3 [1]). The plastic compressive stain of the DUCTAL® FO is limited to $\varepsilon_{cud} = 2.40‰$.

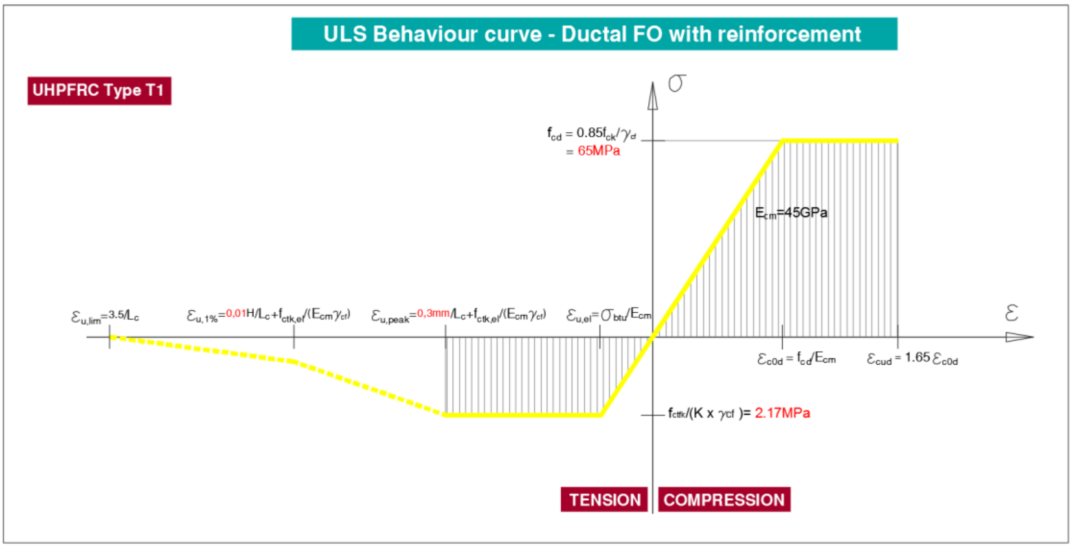

Figure 5: ULS constitutive curve – Ductal FO with reinforcement

The constitutive curves can be understood with the following comments:

- **F1**: For thick element, at the plastic range, the elongation is limited by a factor depending of the height of the element (2/3 h). This rough factor is resulting from the observation of the position of the cracking along the element (almost every 2/3h).
- **F2**: When the thickness of the element is under 3 × Lf (thin element) the contribution of the tensioned Ductal can only be taken into account if the tensile deformation along the medium fiber is not greater than $\varepsilon_{u,lim}/2$
- **F3**: In case shear and tension occur in the same section (continuous beam for example), the designer mustn't take in account two times the same fiber.

Although several methods in the use of UHPC Organic fibers in architectural design have been developed [3-4], we have compared for this project UHPFRC FM and FO design process. The following arguments were analyzed: calculation (Fig. 6), technological (Fig. 7) and construction (Fig. 8) processes. From this analysis, we have developed for the Shum Yip Upperhills project a design method for the feasibility and design development stages.

<table>
<tr><th></th><th colspan="6">UHPFRC CALCULATION PROCESS / ROUGH SYNTHESIS</th></tr>
<tr><th></th><th>BENDING ELASTIC ANALYSIS</th><th>BENDING POST ELASTIC ANALYSIS</th><th>REBAR CONTRIBUTION</th><th>SHEAR ANALYSIS</th><th>DEFLECTION CONTROL</th><th>CRACK CONTROL ANALYSIS</th></tr>
<tr><td>UHPFRC DUCTAL FO</td><td>Average tensile bending stress with a safety factor of 3</td><td>Using stress crack width law</td><td>Depending on the design but this must remain local reinforcement</td><td>Considering fibers contribution</td><td rowspan="2">Calculation in a non cracked section
With a specific material behavior law</td><td rowspan="2">Condition of non brittleness</td></tr>
<tr><td>UHPFRC DUCTAL FM</td><td>Following Code</td><td>Using stress crack width law</td><td>Following codes</td><td>Considering fibers contribution / section contribution / rebars contribution</td></tr>
</table>

Figure 6: Rough synthesis of UHPFRC calculation process

<table>
<tr><th></th><th colspan="6">UHPFRC TECHNOLOGICAL KEY POINTS / ROUGH SYNTHESIS</th></tr>
<tr><th></th><th>ENVIRONMENTAL CLASSES</th><th>MINIMUM THICKNESS AND WIDTH</th><th>PANEL DEAD WIEGHT TRANSFER</th><th>REBAR REINFORCEMENT</th><th>PANEL ANCHORAGE STRATEGY</th><th>HEAT TREATMENT</th></tr>
<tr><td>UHPFRC DUCTAL FO</td><td rowspan="2">If using reinforcing Ductal checking covering of rebar</td><td rowspan="2">30 mm (poured with no reinforcement) / 35mm (pourded with reinforcement) / 15 mm (spraid) / fiber length limit</td><td rowspan="2">If possible consider isostatic transfer to the primary structure.</td><td>To be used rarely. Cracking risk analysis</td><td rowspan="2">Connection systems have to allow both for thermal expansion and fitting tolerane</td><td rowspan="2">Rarely used in everyday project</td></tr>
<tr><td>UHPFRC DUCTAL FM</td><td>Acceptable and justified solution</td></tr>
</table>

Figure 7: Rough synthesis of UHPFRC technological key points

<table>
<tr><th></th><th colspan="6">UHPFRC CONSTRUCTION PROCESS SPECIFICITIES / ROUGH SYNTHESIS</th></tr>
<tr><th></th><th>FORMWORK STRATEGY</th><th>HEAT TREATMENT</th><th>SHRINKAGE QUESTION</th><th>CONSTRUCTION STAGE ANTICIPATION</th><th>PREFABRICATION VERSUS PULLED ON SITE</th><th>UNEXPECTED EVENTS</th></tr>
<tr><td>UHPFRC DUCTAL FO</td><td rowspan="2">Complexity of the molds / number and repetition of the molds</td><td rowspan="2">Ralely used in everyday projects / depending of the dimension and contractof capacity</td><td>0.8 mm/m. Almost all the shrinkage at the beguinning</td><td rowspan="2">The anchorage used for construction stage must be different. The construction step must be checked with the contractor</td><td>Only prefabrication.</td><td>Deflexion during molded process / unexpected cracking near reinforcement</td></tr>
<tr><td>UHPFRC DUCTAL FM</td><td>0.5 mm/m. Almost all the shrinkage at the beguinning</td><td>Prefabrication and pulled on site for specific structural element</td><td>corrosion / unexpecting cracking near reinforcement</td></tr>
</table>

Figure 8: Rough synthesis of UHPFRC construction process specificities

3. FEASIBILITY STUDY DESIGN STAGE

To cross the specificity of the material (included the anchorage question) and the design the feasibility stage includes:

- 1- Choice of material regarding the subject
- 2- Geometrical strategy
- 3- Supports strategy
- 4- Design risk regarding crack analysis
- 5- Construction process strategy
- 6- Preliminary calculation
- 7- Synthesis

The initial design proposed by the design team was considering a peripherical frame and twisted interior independent vertical elements. It is important to precise that, regarding the specific condition of the building site, the panel must be designed for extreme wind load (extreme value of 2.6 kN/m²), thermal loads and seismic action.

From a structural point of view, the twisted shape and the slenderness of each vertical components make the entire system more susceptible and vulnerable to the lateral load (especially the wind load and seismic action). Moreover, the disassociation of each vertical element, which characterize the initial design (Fig. 9-Left) is not efficient especially because of the rotation of the inertia due to Architectural design. As a result, we have proposed, at this stage two additional reinforced horizontal sections at the end of the feasibility study stage (Fig. 9-Right).

The model is then calculated with the following two steps:

- 1 / Linear analysis for UHPFRC/Ductal FO sections
- 2 / Nonlinear analysis for UHPFRC/Ductal FO sections with reinforcement.

The resulting reduction in deflection is illustrated Fig. 10.

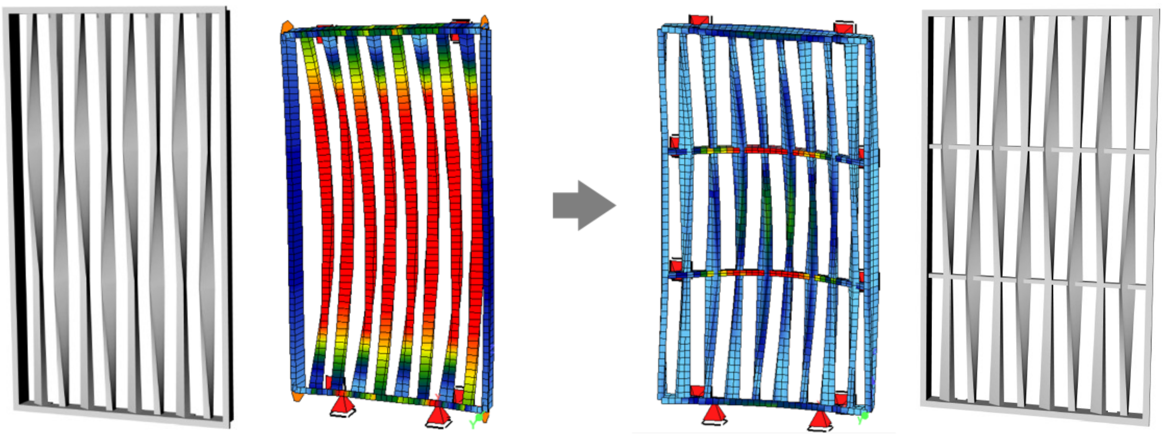

Figure 9: Deflection analysis of two solutions during the feasibility study stage

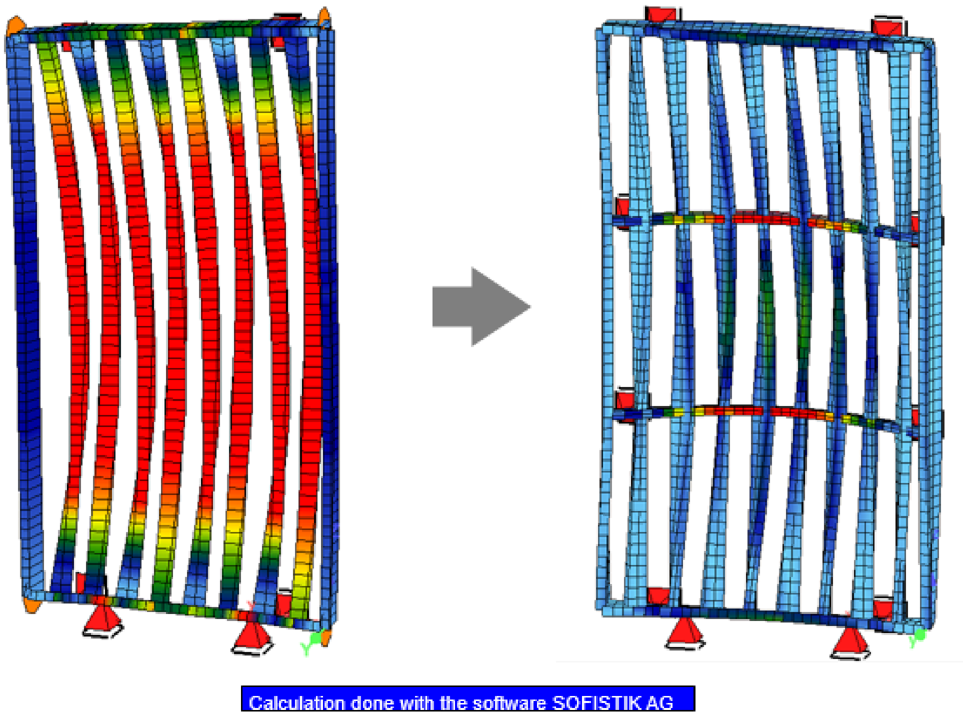

Figure 10: Deflection analysis of two solutions during the feasibility study stage

4. DESIGN DEVELOPMENT

The Structural analysis done during the design development is realized combining UHPFRC/Ductal FO without reinforcement and with local reinforcement. The unreinforced section of Ductal FO should conform to the following criteria under service limit state:

- Maximum compressive stress $\sigma_{bc} \leq 0{,}6 \times f_{ck} = 60$ MPa
- Maximum tensile stress $\sigma_{bt} \leq f_{ctk,el} / 1.6 = 4.3$ MPa (Value from the ID card of Lafarge)
- The opening of cracks was prohibited by limiting the tensile stress at the elastic stage of the behavior.

The Reinforced sections of Ductal FO should conform to the following criteria:
Under serviceability limit state:

- Maximum compressive stress $\sigma_{bc} \leq 0{,}6 \times f_{ck} = 60$ MPa
- Maximum tensile stress $\sigma_{bt} \leq f_{ctfk} / K_{global} = 2.81$ MPa (Limit of plastic stage of the constitutive curve)
- The opening of cracks in the sections is controlled by limiting the elongation in the behavior curve (Fig. 4)
- Limit of deflection $w_{tot} \leq l / 500$

Under ultimate limit state:

- Maximum compressive stress $\sigma_{bc} \leq 0.85 \times f_{ck} / \gamma_{bf} = 65$ MPa

- Maximum tensile stress $\sigma_{bt} \leq f_{ctfk} / (K_{global} \cdot \gamma_{cf}) = 2.17$ MPa
- Maximum shear stress $V_{Ed} \leq V_{Rd,c} + V_{Rd,f} = \dfrac{0.24}{\gamma_{cf}\gamma_E} k f_{ck}^{1/2} b_w z + \dfrac{b_w z \cdot \sigma_{Rd,f}}{\tan\theta}$

with $\gamma_{cf}\gamma_E = 1.5$ and $\tan\theta = 1$

$$\sigma_{Rd,f} = \frac{1}{K_{Local} \times \gamma_{cf} \times w_{0,3}} \int_0^{w_{0,3}} \sigma_{(w)} dw = \frac{\sigma_{(w0,3)}}{K_{Local}} = 2.11 MPa$$

b_w is the smallest width of the cross-section in the tensile area [m]

z is the inner lever arm.

The structure is modelled by beam elements. Connections between interior vertical elements and peripherical frame are fixed (the reinforcements are continuous). Connections between ribbons of peripherical frame are fixed as well. The finite element analysis is done with the software SOFISTIK®, using the modules ASE (General Static Analysis of Finite Element Structures), AQB (Design of cross section). The iterative calculation takes into account the geometrical non-linearity (2[nd] order) and the material non-linearity with the constitutive law described in section 2. The geometry of the panel is defined Fig. 11:

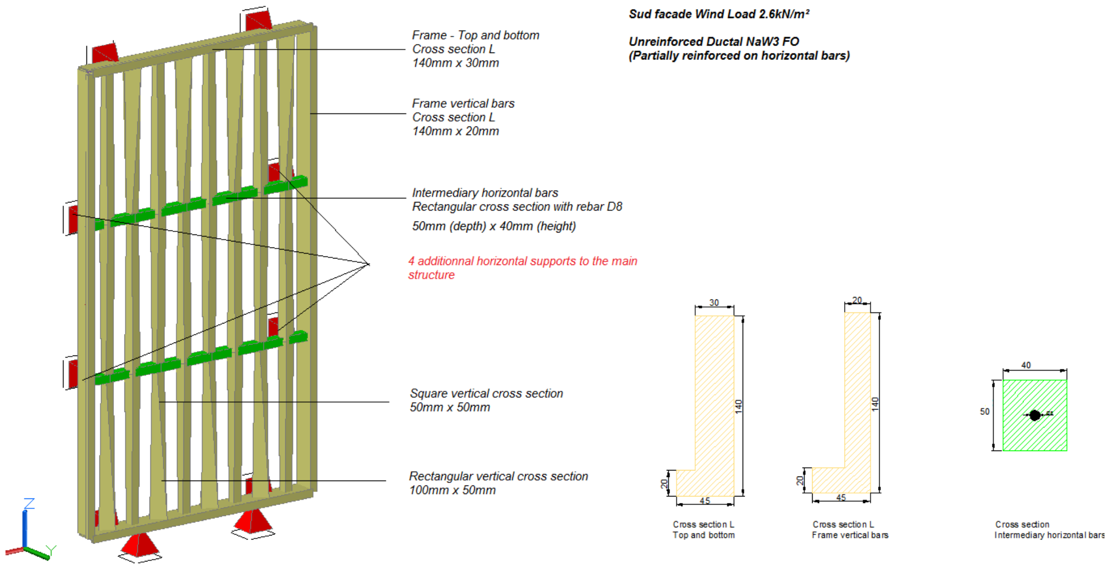

Figure 11: Cross sections

Concerning the Service limit state (SLS): the stresses in the UHPC are lower than the allowable limits described in section §2. The distribution of stresses in the cross-section shown in the graphic result of Sofistik is linear as defined in the design hypothesis (Figs. 12-13). The crack opening is controlled by limiting the elongation at $\varepsilon_{(0,05mm)} = 0{,}05mm / L_C + f_{ctk,el} / E_{cm} = 0.604‰$ on the constitutive curve.

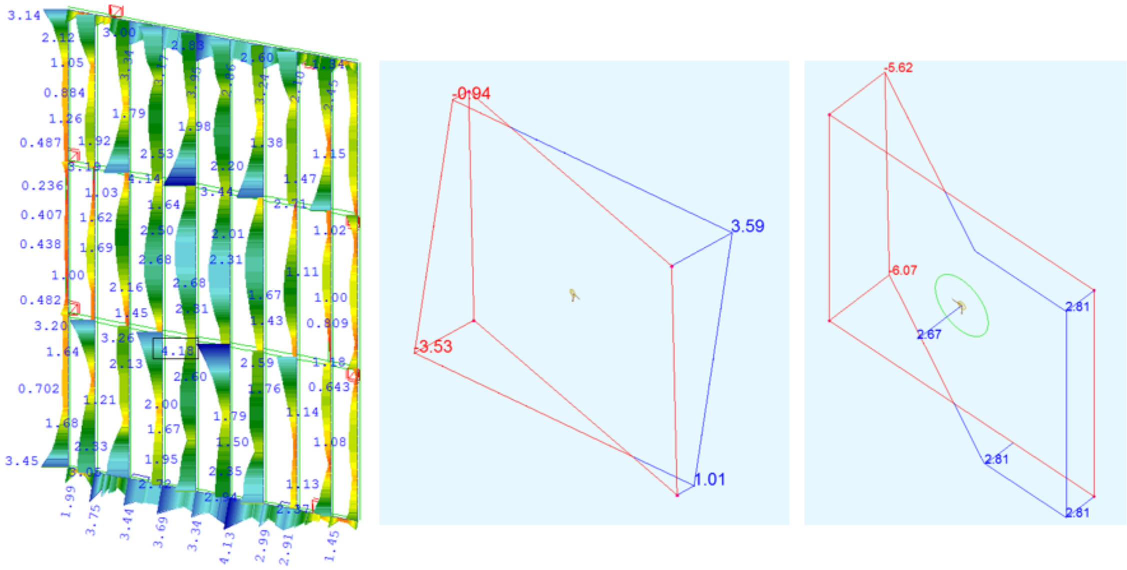

Figure 12: From left to right: Maximum tensile stress under SLS combination on unreinforced cross-section <4.3MPa / Linear axial stress distribution of Unreinforced cross-section - SLS / Non-linear axial stress distribution of Reinforced cross-section - SLS

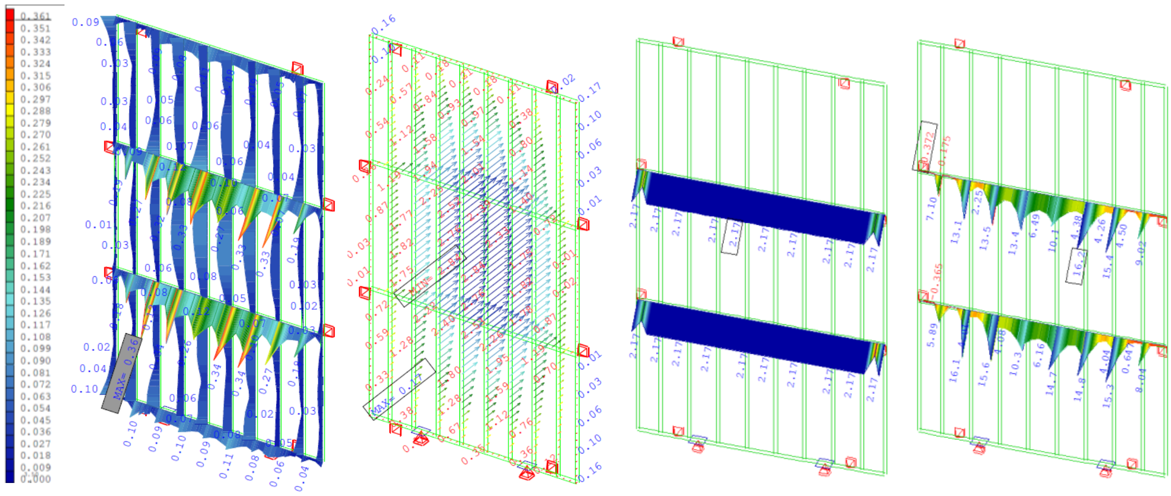

Figure 13: From left to right: Maximum elongation under SLS combination < 0.604‰ / Maximum displacement under SLS combination < L/500=5.6mm / Maximum tensile stress and maximum compressive stress in reinforcement under ULS combination

5. CONSTRUCTION PROCESS BY INJECTION MOULDING

The injection moulding system has been used for the panel construction process (Fig. 14). It leads to the generation of extruded geometries. These geometries are obtained from a linear wire-frame network. The injection molds must, of necessity, be watertight. Thus, they have at least one removable side in order to install the horizontal rebars. The entire façade can thus be created with a very few number of mold.

Figure 14: Construction process from Ever Grow Ltd

6. CONCLUSION

The last decade has seen an expansion of facades with complex geometries. The UHPFRC façade panels that have been designed for Shum Yip Upperhills Loft, are an example of complex geometrical panel design combining geometry with locally reinforced UHPFRC Organic Fibers DUCTAL® NaW3 FO STT. This project was an opportunity to compare UHPFRC FO and FM design process and to try to define a particular design process for organic fibres UHPFRC.

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